



Head Stabilization Measurements As A Potential Evaluation Tool for Comparison of Persons With TBI and Vestibular Dysfunction With Healthy Controls

**Pinata H. Sessoms
Kim R. Gottshall
Jordan Sturdy
Erik Viirre**



Naval Health Research Center

Report No. 14-03

The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government. Approved for public release: distribution is unlimited.

This research has been conducted in compliance with all applicable federal regulations governing the protection of human subjects in research.

**Naval Health Research Center
140 Sylvester Road
San Diego, California 92106-3521**

Head Stabilization Measurements as a Potential Evaluation Tool for Comparison of Persons With TBI and Vestibular Dysfunction With Healthy Controls

Pinata H. Sessoms, PhD*; Kim R. Gottshall, PT, PhD†; Jordan Sturdy, BSE*; Erik Viirre, MD, PhD‡

ABSTRACT A large percentage of persons with traumatic brain injury incur some type of vestibular dysfunction requiring vestibular physical therapy. These injuries may affect the natural ability to stabilize the head while walking. A simple method of utilizing motion capture equipment to measure head movement while walking was used to assess improvements in head stabilization of persons undergoing computerized vestibular physical therapy and virtual reality training for treatment of their vestibular problems. Movement data from the head and sacrum during gait were obtained over several visits and then analyzed to determine improved oscillatory head movement relative to the sacrum. The data suggest that, over time with treatment, head stabilization improves and moves toward a pattern similar to that of a healthy control population. This simple analysis of measuring head stability could be transferred to smaller, portable systems that are easily utilized to measure head stability during gait for use in gait assessment and physical therapy training.

INTRODUCTION

Head stabilization is the active process of keeping the head oriented in an equilibrium position during a particular activity. Normally, when a person walks, the body adjusts to reduce movement of the head (Fig. 1).¹ This helps to maintain balance and reduce the eye motion needed to keep images focused and steady. Because of the functional importance of head stability, accelerations and vertical translations are smaller at the head when compared to the pelvis, trunk, and neck.²⁻⁴ This relative stability of the head allows the visual and vestibular systems to maintain a constant height above the ground while walking.⁵ Previous research has shown that decreased head stability can occur from both pathologic and nonpathologic variables when standing or walking. Nonpathologic conditions include changes in walking speed,⁶ joint fatigue,⁴ or age.⁷ Pathologic conditions include gait following stroke,⁸ visual impairments,⁹ and vestibular dysfunction.¹⁰⁻¹²

In a recent report, over 250,000 U.S. military personnel have been reported to have had some type of traumatic brain injury (TBI)¹³ between 2000 and 2012, with many blast

related, but others as a result of motor vehicle accidents and falls. Over 82% of these injuries are classified as a mild TBI (mTBI),¹³ which is defined as an injury to the head as a result of blunt trauma or acceleration or deceleration of forces that result in any period of transient confusion, disorientation, or impaired consciousness; dysfunction of memory around the time of injury; observed signs of other neurological or neuropsychological dysfunction; or loss of consciousness lasting less than 30 minutes.¹⁴ Some people may be unaware that they have a mTBI which affects them,¹⁵ but the effects of blast trauma are wide reaching and affect many functional systems including vision, concentration, and learning. These injuries may impede sensory integration that interferes with the ability to ambulate without imbalances or the need for aids or corrective devices. Lack of stability may increase risks of falls and further injury, or at the least, impair their ability to recover sufficient function needed to return to duty.

This study proposes to help understand stability and ambulation of persons with mTBI using simple measurements of head stabilization in the sagittal plane. Changes in stabilization of the head could be correlated to successful rehabilitation and improvement in ambulation. Ultimately, it is hoped that examination of this type of data—for differences in head stability in these individuals compared with a healthy control group—might lead to a useful clinical tool that requires no baseline metric obtained preinjury for screening of vestibular dysfunction in persons receiving gait assessments.

METHODS

Patient Population

Subjects were recruited at Naval Medical Center San Diego's (NMCSD) Comprehensive Combat and Complex Casualty Care (C5) facility. Subjects were NMCSD patients (age 23–42 years) having a mTBI that occurred within the past year and who presented at the physical therapy clinic for vestibular

*Warfighter Performance Department, Naval Health Research Center, 140 Sylvester Road, San Diego, CA 92106.

†Physical Therapy Department, Naval Medical Center San Diego, 34800 Bob Wilson Drive, San Diego, CA 92134.

‡Department of Neurosciences, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093.

This article was presented at the Military Health System Research Symposium, Fort Lauderdale, Florida, August 14, 2013.

Approved for public release; distribution is unlimited. This research was conducted in compliance with all applicable federal regulations governing the protection of human subjects (Protocol NHRC.2011.0027, NHRC.2009.0007, and NHRC.2009.0018).

The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government.

doi: 10.7205/MILMED-D-14-00386

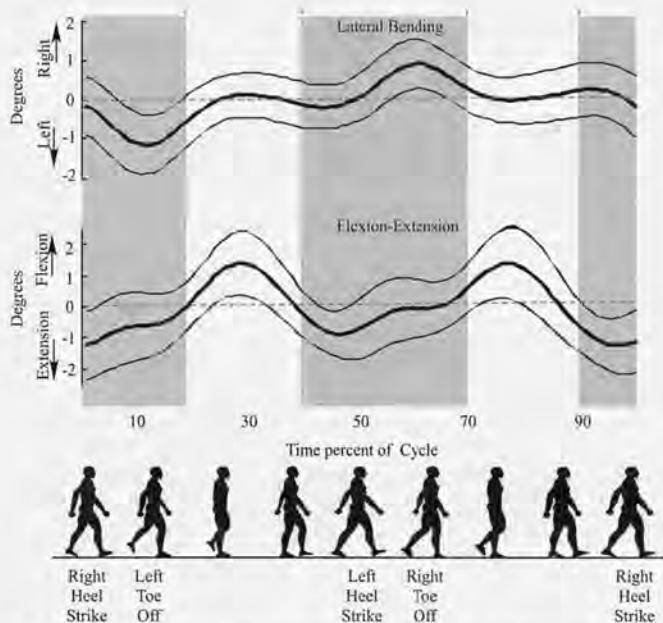


FIGURE 1. Example of head motion data captured during a gait cycle (adapted).¹ The dark line represents the average across subjects, and the lighter lines represent ± 1 SD.

physical therapy. Brain injury was previously diagnosed by attending physicians from one of the U.S. service branches. NMCSD patients, who had severe limits to mobility (i.e., who could not walk without use of a walker, cane, prosthesis, or orthosis), visual dysfunction in which they could not view the screen used during rehabilitation, or were unable to tolerate a 6-week exercise program, were excluded from the study. Those using a prosthesis or orthosis were not included for this head stabilization analyses as it would potentially add more variation to head stabilization than the vestibular dysfunction itself. Volunteers gave written informed consent in accordance with NHRC's Institutional Review Board.

Participants underwent a 6-week, 12-session vestibular physical therapy program utilizing NMCSD's C5 Physical Therapy Department as well as Naval Health Research Center's (NHRC) Computer Assisted Rehabilitation Environment (CAREN).^{16,17} Twice weekly sessions were arranged so that 1 session each week was at NMCSD and the other was on the CAREN at NHRC. Exercises integrated somatosensory, visual, and vestibular systems, as well as some training with cognitive tasking. The vestibulo-ocular reflex, cervico-ocular reflex, depth perception, somatosensory training, dynamic gait, and aerobic function were targeted using tasks such as treadmill walking, head turning, and exercises requiring the subject to move up and down. Exercise difficulty within the C5 clinic at NMCSD was increased by narrowing the base of support, utilizing uneven surfaces, performing with eyes closed, and increasing the velocity of the head or target object motion. CAREN treatment included interactive applications that utilized platform tilts and shifts while the subject walked on the treadmill and was given cognitive tasks such as the Stroop test, math equations, and target acquisition. Difficulty

increased by increasing treadmill speed or walking time, adding additional cognitive tasks, and increasing platform motion. Therapy sessions at each site lasted approximately 20 to 30 minutes.

Head stabilization measurements were acquired when subjects attended a CAREN session. Gait data were acquired while the patient walked on the CAREN treadmill at their self-selected walking speed. Walking speed was set by the subject using a wireless hand controller to increase or decrease the treadmill speed until a comfortable speed was achieved that the subject could walk at for around 5 minutes. Subjects were able to become comfortable with their environment and system before data were collected. Motion capture data were collected using a 12-camera Raptor-E optical motion capture system (Motion Analysis Corporation, Santa Rosa, California) recorded at 120 Hz. Position data were collected from reflective markers placed on the front (middle of forehead) and back (at the same vertical level from the front head marker when the subject was looking straight ahead) of the head as well as the sacrum. Marker data were also collected from heel (middle of the calcaneus), toe (head of fifth metatarsal), and lateral malleolus markers. Ground reaction forces from force plates under each belt (left and right) of the split belt treadmill were used to distinguish initial contact and toe-off times for determining gait cycles. Approximately 10 to 15 seconds of data were obtained. Data were analyzed at three time points during the therapy—week 1 (T1), week 3 (T2), and week 6 (T3)—to measure changes in head stabilization over time.

For a comparison to a currently used clinical measurement used to assess improvements in vestibular function, the Functional Gait Assessment (FGA) score was also obtained at the same three time points. This test assesses postural stability during a 10-item walking task (e.g., walking with changing speeds, walking backward, gait with eyes closed), each item scored on an ordinal scale from 0 to 3. The maximum total score on the test is 30.

Control Group

Head stabilization data from a noninjured control group were also obtained to compare with the vestibular group. The control subjects had no prior TBI or head injury reported or known musculoskeletal injuries or surgeries affecting their gait. They were asked to choose a comfortable self-selected walking speed (using a wireless hand controller) while walking in a virtual hallway scene in the CAREN. Subjects were able to become acclimated to their environment and system before data were collected, approximately 5 to 10 minutes, similar times to those reported for walking on treadmills^{18–20} and within virtual reality environments.^{21,22} Similar motion capture data from the head and sacrum, as well as feet and ground reaction forces were acquired as described for the vestibular patient group. Data were obtained at only one time point for the control group. Volunteers gave written informed consent in accordance with NHRC's Institutional Review Board.

Data Analyses

Motion capture positional marker data were filtered using a fourth-order bidirectional low pass Butterworth filter with cut-off frequency at 6 Hz (Visual 3D, C-Motion, Germantown, Maryland). Overall head position (OHP, or generalized sagittal head angle) was determined as the vertical component of the difference between the position of the front head marker and the back head marker. This value was compared with the vertical position of the sacral marker, which is representative of the body's center of mass (BCOM). Position data for the walking trials were averaged over a full gait cycle (heel contact to ipsilateral heel contact) for each subject, and time in the gait cycle (as a percentage of the full gait cycle) at which the maximum sacral position and minimum overall head position occurred were obtained. To separate data between deficient and nondeficient side, data for the first half of each gait cycle were analyzed for the left and right sides of each subject and categorized as stepping with the side with vestibular deficiency (determined using Dynamic Visual Acuity Test results within the subject's medical record) or nondeficient side. The absolute values of the difference in timing between the sacral maximum and the OHP minimum were termed "OHP offset" and were used as a measure of how "out-of-phase" the two movements were. Values were obtained for each subject during each gait cycle, and mean \pm standard deviation (SD) values were calculated for each subject. Amplitude ranges for OHP and sacral positions were calculated for each subject by subtracting the lowest value of each measure from its highest value through the first 50% of the gait cycle. Mean data for all subjects were then calculated from these data.

Statistical Analyses

A two-factor repeated-measures analysis of variance was conducted to compare the differences in head and sacral motion peak timing over the gait cycle as well as the OHP offset for the vestibular group. The two independent variables were time (T1, T2, and T3) and side (side with vestibular

deficit, nondeficient side). Independent samples *t*-tests were conducted to compare differences in head and sacral motion peak timing over the gait cycle as well as the OHP offset between the vestibular group (for each time point) and the control group. A Pearson product-moment correlation analysis was performed between OHP offset and FGA scores collected at all time points to determine if a relationship existed between the two measures. Standard statistical software (IBM SPSS, Armonk, New York) was used. Statistical significance was defined as $p \leq 0.05$.

RESULTS

Data from 10 male military members (mean \pm SD age: 31.3 ± 5.9 years; mean \pm SD height: 173.5 ± 8.5 cm; and mean \pm SD weight: 87.1 ± 12.5 kg) with diagnosis of vestibular disorder as a result of mTBI were examined. Individual characteristics for each patient including the number of days since injury and start of the intervention (at T1), as well as main side of vestibular deficiency and mechanism of injury are reported in Table I. Control group data were obtained from 15 healthy, active duty male military personnel (mean \pm SD age: 30.9 ± 6.5 years, mean \pm SD height: 175.6 ± 9.1 cm, and mean \pm SD weight: 81.1 ± 13.3 kg).

Amplitude Ranges and Walking Speed

Mean amplitude ranges for the vestibular group's sacral marker movement were less than those of the control group, though the amplitudes increased and moved closer to the control group over the 3 time points. Mean \pm SD amplitude ranges of the sacral marker movement were as follows: T1 = 1.2 ± 0.7 cm, T2 = 2.6 ± 1.1 cm, T3 = 2.9 ± 1.0 cm, and control = 2.8 ± 0.6 cm. Mean amplitude ranges of the vestibular group's OHP decreased over time and also approached the values measured in the control group; mean \pm SD amplitude ranges were 0.48 ± 0.35 cm, 0.58 ± 0.19 cm, 0.37 ± 0.28 cm, and 0.40 ± 0.22 cm, for T1, T2, T3, and control, respectively. Additionally, mean walking speeds of the vestibular group approached those of the control group—starting at

TABLE I. Individual characteristics for each patient participating in vestibular therapy study. Side of vestibular deficiency (L = left, R = right) was determined using Dynamic Visual Acuity Test results. Mechanism of injury was either due to motorcycle accident, improvised explosive device (IED), fall, concussion while playing a sport, or motor vehicle accident (MVA).

Sex	Age (Years)	Height (cm)	Weight (kg)	Days Since Injury and Start of Intervention (T1)	Side of Vestibular Deficiency	Mechanism of Injury
Patient 01	M	27	180.34	88.5	123	R
Patient 02	M	37	175.26	75.3	153	L
Patient 03	M	27	185.42	120.2	263	R
Patient 04	M	29	160.02	81.6	85	R
Patient 05	M	23	165.10	83.9	316	L
Patient 06	M	31	167.64	77.1	197	R
Patient 07	M	33	167.64	82.6	266	L
Patient 08	M	42	175.26	89.8	105	R
Patient 09	M	27	172.72	86.2	259	R
Patient 10	M	37	185.42	86.2	124	L
Mean (SD)	31.30 (5.89)	173.48 (8.56)	87.14 (12.50)	189.10 (81.82)		Sport

0.65 m/s at T1, increasing to 0.81 m/s at T2, and measuring at 1.01 m/s at T3. Control group velocity was 1.11 m/s.

Timing of OHP and Sacral Peaks

Mean values of timing (as a percent of the gait cycle) at which the maximum vertical sacral position and minimum vertical OHP position as well as the OHP offset for each subject groups are reported in Table II. For the control group, sinusoidal motion of OHP was observed as it moved antiphase to the vertical motion of the body (Fig. 2). Minimum OHP occurred at approximately the same time in the gait cycle (around 35%) as the maximum vertical position of the sacral marker in the control group. In comparison, for the vestibular group, mean time for minimum OHP values varied between 25% and 32%, whereas the sacral maximum values occurred around 34% to 37% (Fig. 3). Mean time of OHP minimum occurred earlier in the gait cycle than timing of sacral maximum for the vestibular patients. For deficient and nondeficient steps of the vestibular group, neither the OHP minimum nor sacral maximum timings were statistically different between the three time points.

Independent samples *t*-tests were conducted to compare timing of the sacral maximums as well as OHP minimums between the control group and vestibular group at each time point. For the side with vestibular deficit, no significant differences were found for maximum vertical sacral position between the two groups. For the nondeficient side, significant differences were only observed at T3 [$t(23) = 2.491, p = 0.022$]. The magnitude of the differences in the means was relatively large (Cohen's $d = 1.1016$). Minimum vertical OHP position was significantly different between groups for all time points for the side with vestibular deficiency: T1 [$t(23) = 4.030, p = 0.006$], T2 [$t(23) = 3.684, p = 0.001$], and T3 [$t(23) = 2.525, p = 0.019$]. The magnitude of the differences in the means was relatively large for all time points (Cohen's d is 1.499 at T1, 1.432 at T2, and 0.979 at T3). OHP minimums were not significantly different at T1 when walking on the nondeficient side [$t(23) = -2.568, p = 0.051$], but was significant at T2 [$t(23) = 3.499, p = 0.011$] and T3 [$t(23) =$

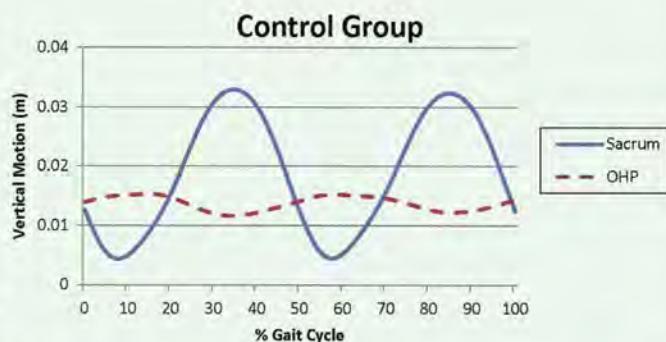


FIGURE 2. Control group sacral and overall head position (OHP) movements over the gait cycle.

3.704, $p = 0.008$]. Large effect sizes were observed for these time points (Cohen's d is 1.316 at T2 and 1.405 at T3).

OHP Offset

The OHP offset displayed more changes between groups. There was little variability between control subjects—timing offsets between head and sacral marker for individuals ranged between 1.3% and 6.8% of the gait cycle apart from each other. Standard deviations between gait cycles for individuals were also fairly low, between 0.83% and 5.8% SD. The mean OHP offset during gait for the control group was about 4% for both the left and right sides. In comparison, mean OHP offset of the patient group was larger, ranging between 8% and 15%, with higher values measured in the side with vestibular deficit, though differences in phase decreased over time. Larger variability in the vestibular group was also observed (Table III). Mauchley's test indicated that assumption of sphericity had been violated for the main effect of time, $c^2(2) = 6.64, p = 0.036$ when determining significant difference in OHP offset for the vestibular deficient side. Therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.64$ for main effect of time and $\epsilon = 1.00$ for main effect of side). There was a significant main effect for time, $F(1.28, 11.51) = 7.71, p = 0.013$, but not for side or interaction between time

TABLE II. Mean and standard deviation (SD, given in parentheses) values of subjects for timing of first maximum sacral position and first overall head position (OHP) minimum position as well as the OHP offset (difference between the timing of Sacral Max and OHP Min) as a percent of the gait cycle. Both the healthy control group and vestibular group at three time points are reported. For the vestibular group, data is reported when the subject took a step on the side with his vestibular deficiency (Deficient side) as well as his side without vestibular deficiency (Nondeficient side). Left and right sides of the control group are also reported for comparison.

Group and Side	Time of Sacral Max M (SD)	Time of OHP Min M (SD)	OHP Offset M (SD)
Control Group Left Side	35.71 (1.82)	35.40 (3.37)	4.03 (2.17)
Control Group Right Side	35.89 (1.95)	36.77 (2.73)	4.15 (1.45)
Vestibular T1 Deficient Side	35.31 (6.61)	24.61 (9.62)*	14.85 (7.83)*
Vestibular T2 Deficient Side	35.07 (2.57)	29.01 (5.35)*	10.53 (4.78)*
Vestibular T3 Deficient Side	34.74 (1.60)	30.95 (5.49)*	10.21 (4.60)*
Vestibular T1 Non Deficient Side	36.81 (5.03)	31.60 (7.12)	11.04 (3.76)*
Vestibular T2 Non Deficient Side	34.83 (2.12)	30.26 (6.44)*	9.82 (2.53)
Vestibular T3 Non Deficient Side	33.85 (1.84)*	30.48 (5.72)*	8.44 (2.32)

*Indicate significant differences between the vestibular group and the control group.

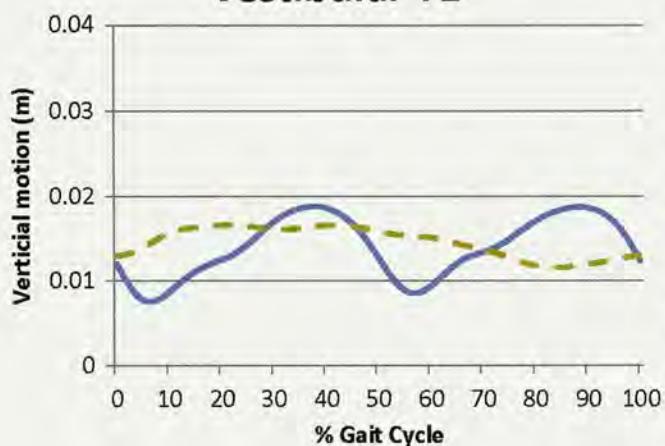
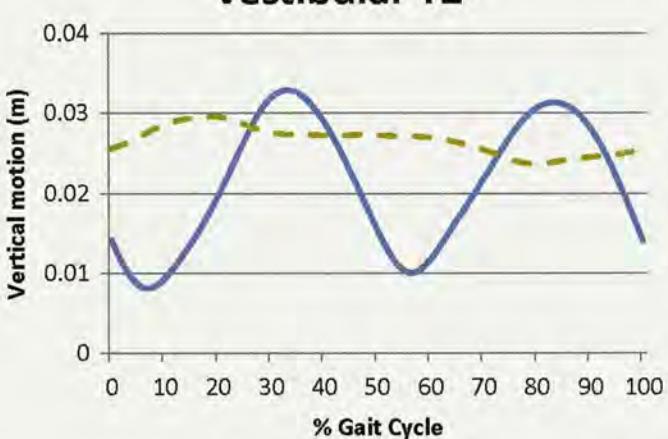
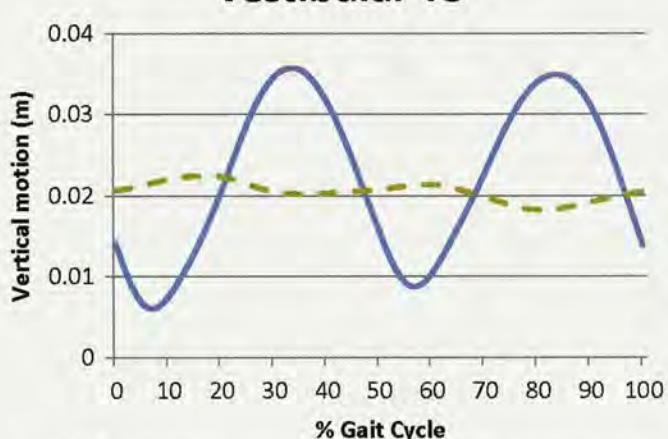
Vestibular T1**Vestibular T2****Vestibular T3**

FIGURE 3. Vestibular group sacral (solid line) and overall head position (dashed line) movements over the gait cycle at the 3 measured time points. Gait cycle starts with subjects taking a step on their side with vestibular deficit, where second half of gait cycle is subjects taking a step on their side without deficit.

and side. Post hoc tests showed a significant difference between T1 and T3 ($p = 0.049$), but not between T1 and T2 or T2 and T3.

Independent samples t -tests were conducted to compare OHP offset between the control group and vestibular group at each time point. For the side with vestibular deficiency (for the vestibular group), there was a significant difference in OHP offset between the control group and vestibular group at T1 [$t(23) = -5.21, p < 0.001$], T2 [$t(23) = -4.883, p < 0.001$], and T3 [$t(23) = -4.809, p < 0.001$]. The magnitude of the differences in the means was relatively large (Cohen's $d > 0.8$) for all time points (Cohen's d is 1.899 at T1, 1.804 at T2, and 1.780 at T3). For the side without vestibular deficiency, there was a significant difference in OHP offset between the control group and vestibular group only at T1 [$t(23) = -5.926, p < 0.001$]. The magnitude of the differences in the means was large (Cohen's $d = 2.284$).

The relationship between OHP offset values and a clinical measurement of vestibular dysfunction (FGA scores) was investigated using Pearson product-moment correlation coefficient. Preliminary analyses were performed to ensure no violation of the assumption of normality, linearity, and homoscedasticity. There was a small, negative correlation between the two variables [$r = -0.29, n = 30, p = 0.117$], with higher OHP offset values associated with lower FGA scores.

DISCUSSION

This is the first study to report head and BCOM relationships of persons with mTBI during gait. For stability of visual imagery while walking, the vertical motion of the head is adjusted by moving antiphase to the body to minimize vertical excursions of the eyes during the gait cycle. As in previous experiments, our data demonstrate the values of head motion were much lower than the sacral movement range for both the vestibular and control groups,²³ indicating that the brain actively controls the body during normal walking to stabilize the head. In general, persons with TBI undergoing vestibular physical therapy seem to have difficulty with head stabilization, as demonstrated with the larger head motion, marked out-of-phase head movement, and larger variability between head and BCOM movement compared to the control group, particularly when measuring the side with vestibular deficit. It appears that, over time and with therapy, head stabilization improves—demonstrated by the improved gait phase tracking—and moves toward a head motion pattern more similar to the control population. This important observation suggests that retraining or adaptation of neuromuscular programmed activity is occurring with vestibular rehabilitation. The increase in gait speed over time for the vestibular group may also play a role in head movement pattern changes. It would be beneficial to compare speed matched controls in future studies.

For the vestibular group, the side without vestibular deficiency showed more similar values in OHP offset to the

TABLE III. Mean overall head position offset and standard deviation (SD, given in parentheses) values for all gait cycles for each patient participating in vestibular therapy at each timepoint and for both the side with vestibular deficiency and side without vestibular deficiency (Nondeficient side). Functional Gait Assessment (FGA) scores at the same timepoints are also reported. Overall mean and standard deviation of all subjects is reported on the last line.

	OHP Offset T1—		OHP Offset T2—		OHP Offset T3—		OHP offset T1— Nondeficient Side	OHP offset T2— Nondeficient Side	OHP offset T3— Nondeficient Side	FGA T1	FGA T2	FGA T3
	Deficient Side	Nondeficient Side	Deficient Side	Nondeficient Side	Deficient Side	Nondeficient Side						
Patient 01	3.89 (2.62)	6.09 (14.29)	6.91 (9.79)	6.88 (4.61)	8.10 (2.56)	8.10 (2.28)	26	30	30	30	30	30
Patient 02	12.27 (8.17)	3.54 (11.78)	8.71 (10.82)	9.73 (6.15)	7.92 (4.19)	8.15 (8.67)	26	28	28	30	30	30
Patient 03	11.88 (8.77)	11.78 (14.52)	9.09 (14.21)	12.57 (8.04)	8.33 (10.72)	7.64 (4.97)	28	30	30	30	30	30
Patient 04	12.00 (7.48)	7.33 (8.74)	8.75 (9.55)	7.40 (2.97)	8.36 (7.46)	5.82 (5.12)	28	30	30	30	30	30
Patient 05	10.00 (5.59)	9.54 (4.79)	8.23 (4.21)	12.75 (9.89)	11.69 (3.57)	10.92 (9.40)	27	30	30	30	30	30
Patient 06	15.14 (14.93)	6.86 (2.04)	5.00 (6.87)	13.00 (12.53)	15.29 (9.71)	10.33 (9.07)	23	27	27	28	28	28
Patient 07	17.86 (8.15)	19.00 (13.14)	18.38 (10.01)	13.50 (6.30)	9.13 (9.83)	6.56 (3.94)	26	30	30	30	30	30
Patient 08	22.83 (14.86)	12.33 (14.53)	18.70 (11.13)	4.33 (4.37)	12.14 (7.58)	4.80 (2.53)	23	28	28	30	30	30
Patient 09	32.00 (12.47)	16.17 (13.74)	10.08 (8.92)	14.20 (6.53)	10.09 (4.68)	10.36 (3.75)	23	30	30	30	30	30
Patient 10	10.60 (9.07)	12.63 (3.66)	8.29 (4.07)	16.00 (6.20)	7.13 (6.85)	11.69 (14.80)	17	23	23	27	27	27
Overall Mean (SD)	14.84 (7.83)	10.53 (4.78)	10.21 (4.60)	11.04 (3.76)	9.81 (2.52)	8.44 (2.32)	24.70 (3.33)	28.60 (2.27)	29.50 (1.08)			

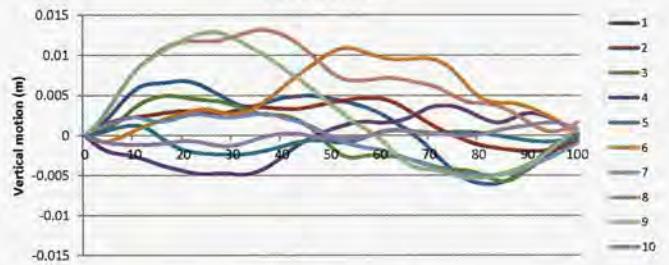
control group compared to the side with vestibular deficiency. This suggests better antiphase patterns between the sacrum and head when taking a step on the sound side compared to the side with vestibular deficit. The sinusoidal pattern of the sacrum was observed for all groups and time points (though amplitude changed), but pattern in OHP was variable for the vestibular group over time. Deficits are most likely because of abnormal head movement at the earlier time points, with an antiphase pattern between the head and BCOM least evident when stepping on the side with vestibular deficit (Fig. 4). Large variations in head movement of the vestibular group made it difficult to determine any clear patterns of movement as a group, suggesting disruption or delay of the neural programs for motor stabilization of the head. OHP movement patterns may be related to the type of vestibular deficit each subject exhibited, and should be explored in future studies. Increasing the sample size of the vestibular patients may also show stronger relationships in OHP offset, head stabilization, and vestibular dysfunction.

The correlation between OHP offset and FGA was small. It is possible the FGA measurement is not sensitive enough for measuring head stabilization or that there was a ceiling effect of the FGA for some vestibular patients in this study (8 of the 10 subjects reached the maximum score at T3). Previous research has shown that the minimal detectable change (pre- to post-treatment change that exceeds chance variation) in persons with balance and vestibular disorders was estimated to be 6 points.²⁴ Only 3 of the 10 patients met this degree of change with a difference of 4.8 points between the overall mean scores at T1 and T3, but this is currently one of the few objective clinical measures involving walking tasks. OHP offset data may help to measure changes in head stabilization that the FGA test may not be sensitive enough to measure. Future work should focus on correlating OHP offset measurements with other clinical head stabilization tests, such as the Dynamic Visual Acuity Test and Gaze Stabilization Test, and how these compare over time with vestibular physical therapy. It would also be beneficial to compare OHP offset data from a similar group of individuals with vestibular dysfunction over time who are not receiving vestibular physical therapy or those receiving targeted head stabilization activities to determine what changes are occurring because of the therapy itself. Finally, further analyses in head and body movement in all three planes of movement (sagittal, coronal, and transverse) may provide a better picture of vestibular deficit.

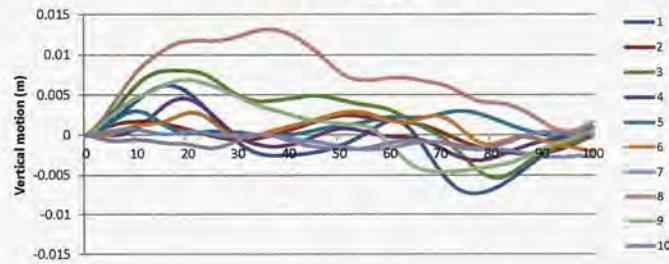
CONCLUSION

This study used a simple measurement of head stabilization to help understand stability and ambulation of persons with mTBI. The data suggest that, over time with treatment, head stabilization improves and moves toward a pattern similar to that of a healthy control population. Although some significance was found in head stabilization measurement,

Vestibular T1



Vestibular T2



Vestibular T3

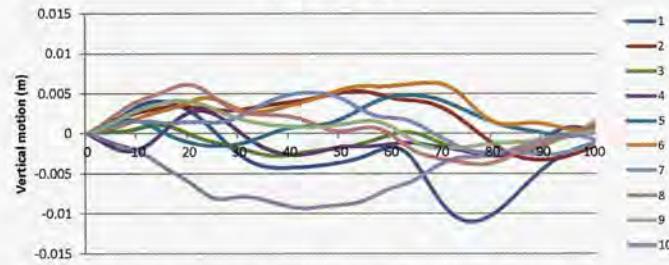


FIGURE 4. Mean overall head position (OHP) (or generalized sagittal head angle) curves for individual vestibular subjects at each time point. Several subjects did not display the double sinusoidal motion (two-hump) pattern as displayed by the control group or that seen with typical normal walking at the earlier time points, but began to display it at later time points. Over time, subjects also showed less bias towards positive OHP motion, and was more centered around neutral (0). Gait cycle starts with subjects taking a step on their side with vestibular deficit, where second half of gait cycle is subjects taking a step on their side without deficit.

OHP offset over time, there was large variability between gait cycles for each subject and between vestibular subjects. This technique of measuring head compared with body movement could be transferred to smaller, portable systems easily utilized in physical therapy training and assessments. Inertial measurement units are small, mobile devices that can be easily placed on the head and torso to get similar data as reported above, but they do not need optical motion capture cameras and associated space requirements. Other small portable camera systems, such as a Kinect (Microsoft Corporation, Redmond, Washington), may also have the potential to measure these movements in a clinical setting. Variability of the head movement patterns, and differences in phase of head movement compared to body movement, may be a way to readily detect head stabilization issues or measure improvements in head stabilization over time and with therapy.

ACKNOWLEDGMENTS

The authors would like to thank John-David Collins, Kathrine Service, Aaron Wolf, and LCDR Jose Dominguez for their contributions to this research study. This work was supported by the Bureau of Medicine and Surgery Wounded, Ill, and Injured grant R116 under work unit no. 60818.

REFERENCES

- Mulavara A, Verstraete MC, Bloomberg JJ: Modulation of head movement control in humans during treadmill walking. *Gait Posture* 2002; 16(3): 271-82.
- Konz R, Fatone S, Gard S: Effect of restricted spinal motion on gait. *J Rehabil Res Dev* 2006; 43(2): 161-70.
- Cromwell RL, Aadland-Monahan TK, Nelson AT, Stern-Sylvestre SM, Seder B: Sagittal plane analysis of head, neck, and trunk kinematics and electromyographic activity during locomotion. *J Orthop Sports Phys Ther* 2001; 31: 255-62.
- Kavanagh J, Barrett R, Morrison S: The role of the neck and trunk in facilitating head stability during walking. *Exp Brain Res* 2006; 172(4): 454-63.
- Kermouian R, Johanson ME, Skinner S: Development of Gait. In *Human Walking*, pp 119-30. Edited by J Rose, JG Gamble. Philadelphia, Lippincott Williams & Wilkins, 2005.
- Latt MD, Menz HB, Fung VS, Lord SR: Walking speed, cadence and step length are selected to optimize the stability of head and pelvis accelerations. *Exp Brain Res* 2008; 184(2): 201-9.
- Van Emmerik RE, McDermott WJ, Haddad JM, Van Wegen EE: Age-related changes in upper body adaptation to walking speed in human locomotion. *Gait Posture* 2005; 22(3): 233-9.
- Lamontagne A, Fung J: Gaze and postural reorientation in the control of locomotor steering after stroke. *Neurorehabil Neural Repair* 2009; 23(3): 256-66.
- Demer JL, Viirre ES: Visual-vestibular interaction during standing, walking, and running. *J Vestib Res* 1996; 6(4): 295-313.
- Whitney SL, Sparto PJ, Hodges LF, Babu SV, Furman JM, Redfern MS: Responses to a virtual reality grocery store in persons with and without vestibular dysfunction. *Cyberpsychol Behav* 2006; 9(2): 152-6.
- Whitney SL, Marchetti GF, Pritchett M, Furman JM: Gaze stabilization and gait performance in vestibular dysfunction. *Gait Posture* 2009; 29(2): 194-8.
- Paquet N, Dannenbaum E, Hakim-Zadeh R, Fung J: Effects of fast head turns on head, trunk and pelvis motions during standing and walking in patients with unilateral vestibular deficit. *J Vestib Res* 2006; 16(6): 279-84.
- Fischer H: U.S. Military casualty statistics: Operation New Dawn, Operation Iraqi Freedom, and Operation Enduring Freedom. Congressional Research Service. 2013: 7-5700. Available at <http://www.fas.org/sgp/crs/hatsec/RS22452.pdf>; accessed October 13, 2013.
- National Center for Injury Prevention and Control. Report to Congress on Mild Traumatic Brain Injury in the United States: Steps to Prevent a Serious Public Health Problem. Atlanta, GA, Centers for Disease Control and Prevention, 2003. Available at <http://www.cdc.gov/ncipc/pub-res/mtbi/mtbireport.pdf>; accessed October 23, 2014.
- Kaufman KR, Brey RH, Chou LS, Rabatin A, Brown AW, Basford JR: Comparison of subjective and objective measurements of balance disorders following traumatic brain injury. *Med Eng Phys* 2006; 28(3): 234-9.
- Gottshall KR, Sessoms PH, Bartlett JL: Vestibular physical therapy intervention: utilizing a computer assisted rehabilitation environment in lieu of traditional physical therapy. *Conf Proc IEEE Eng Med Biol Soc* 2012; 2012: 6141-4.
- Gottshall KR: Vestibular rehabilitation after mild traumatic brain injury with vestibular pathology. *NeuroRehabilitation* 2011; 29: 167-71.
- Lee SJ, Hidler J: Biomechanics of overground vs. treadmill walking in healthy individuals. *J Appl Physiol* 2008; 104(3): 747-55.

19. Riley PO, Paolini G, Della Croce U, Paylo KW, Kerrigan DC: A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait Posture* 2007; 26(1): 17–24.
20. Dingwell JB, Cusumano JP, Cavanagh PR, Sternad D: Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *J Biomech Eng* 2001; 123(1): 27–32.
21. Gates DH, Darter BJ, Dingwell BD, Wilken JM: Comparison of walking overground and in a Computer Assisted Rehabilitation Environment (CAREN) in individuals with and without transtibial amputation. *J Neuroeng Rehabil* 2012; 9: 81.
22. Sheik-Nainer MA, Kaber DB: The utility of a virtual reality locomotion interface for studying gait behavior. *Hum Factors* 2007; 49(4): 696–709.
23. Mulavara AP, Ruttle T, Cohen HS, et al: Vestibular-somatosensory convergence in head movement control during locomotion after long-duration space flight. *J Vestib Res* 2012; 22(2): 153–66.
24. Marchetti GF, Lin CC, Alghadir A, Whitney SL: Responsiveness and minimal detectable change of the dynamic gait index and functional gait index in persons with balance and vestibular disorders. *J Neurol Phys Ther* 2014; 38(2): 119–24.

Copyright of Military Medicine is the property of AMSUS and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.

REPORT DOCUMENTATION PAGE

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB Control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD MM YY) 01 12 13		2. REPORT TYPE Journal Article		3. DATES COVERED (from – to) Jun 2009 – Dec 2013
4. TITLE Head Stabilization Measurements as A potential Evaluation tool for Comparison of Persons with TBI and Vestibular Dysfunction with Healthy Controls		5a. Contract Number: 5b. Grant Number: R116 5c. Program Element Number: 5d. Project Number: 5e. Task Number: 5f. Work Unit Number: 60818		
6. AUTHORS Sessoms, Pinata H., Kim R. Gottshall, Jordan & Erik Vuirre				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Commanding Officer Naval Health Research Center 140 Sylvester Rd San Diego, CA 92106-3521				8. PERFORMING ORGANIZATION REPORT NUMBER 14-03
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES) Commanding Officer Naval Medical Research Center 503 Robert Grant Ave Silver Spring, MD 20910-7500		Chief, Bureau of Medicine and Surgery 7700 Arlington Blvd Falls Church, VA 22042		10. SPONSOR/MONITOR'S ACRONYM(S) NMRC/ BUMED
				11. SPONSOR/MONITOR'S REPORT NUMBER(s)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				
13. SUPPLEMENTARY NOTES <u>Military Medicine</u> , (2015), <u>180</u> (3), 135-142				
14. ABSTRACT A large percentage of persons with traumatic brain injury (TBI) incur some type of vestibular dysfunction requiring vestibular physical therapy. These injuries may affect the natural ability to stabilize the head while walking. A simple method of utilizing motion capture equipment to measure head movement while walking was used to assess improvements in head stabilization of persons undergoing vestibular physical therapy and compared to a healthy control group. Data from the head and sacrum during gait were obtained over several visits and then analyzed to determine improved oscillatory head movement relative to the sacrum (representative of the body center of mass BCOM). For the control group, sinusoidal motion of overall head position (OHP) was observed as it moved antiphase to the vertical motion of the BCOM, displaying good head stabilization characteristics. The OHP offset of the group having a TBI did not show the same patterned motion as the control group but over time and with training, more closely resembled that of the control group. Mean walking speeds of the vestibular group approached those of the control group over time. The data suggest that, over time with therapy, head stabilization improves and moves toward a pattern similar to that of a healthy control population. This simple analysis of measuring head stability could be transferred to smaller, portable systems that are easily utilized in physical therapy training and assessments.				
15. SUBJECT TERMS CAREN, vestibular therapy, TBI, gait, head stabilization				
16. SECURITY CLASSIFICATION OF: a. REPORT UNCL		17. LIMITATION OF ABSTRACT UNCL	18. NUMBER OF PAGES 10	18a. NAME OF RESPONSIBLE PERSON Commanding Officer
				18b. TELEPHONE NUMBER (INCLUDING AREA CODE) COMM/DSN: (619) 553-8429

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18